Diversity and MIMO Performance Evaluation of Common Phase Center Multi Element Antenna Systems

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Abstract. *The diversity and Multiple Input Multiple Output (MIMO) performance provided by common phase center multi element antenna (CPCMEA) systems is evaluated using two practical methods which make use of the realized active element antenna patterns. These patterns include both the impact of the mutual coupling and the mismatch power loss at antenna ports. As a case study, two and four printed Inverted F Antenna (IFA) systems are evaluated by means of Effective Diversity Gain (EDG) and Capacity (C). EDG is measured in terms of the signal-to-noise ratio (SNR) enhancement at a specific outage probability and in terms of the SNR reduction for achieving a desired average bit error rate (BER). The concept of receive antenna selection in MIMO systems is also investigated and the simulation results show a 43% improvement in the 1% outage C of a reconfigurable 2x2 MIMO system over a fixed 2x2 one.*

Keywords

Antenna diversity, bit error rate, effective diversity gain, MIMO capacity, printed circuit antennas, receive antenna selection.

1. Introduction

The need for more robust communication links and increased data rates are issues of primary importance for nowadays wireless communications systems. Diversity and Multiple Input Multiple Output (MIMO) systems, formed using multi-element antennas (MEA), can be used as a remedy for these issues, owing to their ability to both combat and exploit multipath fading. A need in many nowadays MEA designs is to integrate the antenna elements onto compact terminal devices e.g. [1]-[5]. A MEA system, designed for such devices, comprises coupled antenna elements which share the same ground plane. As a result when one element is excited the whole device (including the non-excited elements) contributes to the quality and quantity of radiation. Hence, for this type of MEA, a common phase center, defined at the origin of the array coordinate system, should be used for all antenna elements [6]. Hereafter, this kind of MEA systems is called common phase center MEA (CPCMEA).

Computational methods for evaluating the diversity and MIMO performance of CPCMEA would be very attractive since they avoid the expensive measurement approach [5], [7] and offer a convenient way to compare different antenna designs. Regarding diversity systems, a simple and practical method for evaluating the Effective Diversity Gain (EDG) of CPCMEA is presented in [8] for the special case of 2-port antennas letting the general case for M-port antennas unaddressed. On the other hand, justified models for Capacity (C) evaluation e.g. [9], [10] in their present form apply only for arrays comprising elements with different phase centers. Moreover these models are impractical since they require a large number of statistical input parameters, most of which can only be obtained by measurements or extended ray-tracing simulations. Alternatively, it has been proved in [11], [12] that even a simple single-bounce propagation model can provide sufficiently accurate capacity estimation if the antenna properties are treated properly.

In this study, two simple and practical methods for evaluating the receiving diversity and MIMO performance of CPCMEA are presented. Diversity performance is evaluated under the maximum ratio combining (MRC) scheme using a practical method that utilizes the complex correlation coefficient (ρ) and the mean effective gains (MEG) [13] of the M-port CPCMEA. This method is the generalization of that presented in [8], which applies only for 2-port CPCMEA systems. MIMO performance on the other hand is evaluated using a generic MIMO model [10], which is simplified under a single bounce propagation scenario and modified to apply for CPCMEA. This model is then applied to quantify the performance of both fixed and reconfigurable MIMO systems formed under the concept of antenna selection [14]. Both methods use the realized (i.e. mismatch power losses are included) active (i.e. mutual coupling is implicitly included [6]) antenna element patterns.

The paper is organized as follows. Section 2 provides the description of the practical methods for evaluating the diversity and MIMO performance of CPCMEA systems. In Section 3 the description of the investigated two and four printed inverted F antenna (IFA) structures, sharing the same ground plane, is presented. The simulated diversity and MIMO performance results are presented and discussed in Section 4. The noteworthy remarks of this study are summarized in Section 5.

2. Evaluating the Performance of Common Phase Center MEA

The methods for diversity and MIMO performance evaluation of CPCMEA are presented in this section. The diversity performance is evaluated under the MRC scheme by means of the achieved EDG in terms of a) the signal-to-noise ratio (SNR) enhancement at a specific outage probability and b) the SNR reduction for achieving a desired average BER. The MIMO system performance is evaluated by means of its Capacity (C) assuming no channel state information (CSI) at the transmitter.

2.1 Diversity Performance Evaluation

Both the MEG of each antenna element and the complex correlation coefficients (ρ) between their received signals have been used extensively for diversity performance evaluation. MEG_m is defined as the ratio of the average power received at the m^{th} port of an M-port antenna system over the mean incident power on the antenna system and can be calculated by [13]

$$MEG_m = \int \left(\frac{X}{X+1} G_{\theta m} P_\theta + \frac{1}{X+1} G_{\varphi m} P_\varphi \right) d\Omega \tag{1}$$

where X is the cross polarization discrimination, G_θ and G_φ are the θ and φ polarized components of the antennas' realized active power gain patterns and P_θ, P_φ are, respectively, the θ and φ components of the angular density functions of the incoming plane waves. The complex correlation coefficient between the signals at the m^{th} and n^{th} ports can be calculated by [13]

$$\rho_{nm} = \frac{\oint \left(X \cdot E_{\theta n} E_{\theta m}{}^{*} P_\theta + E_{\varphi n} E_{\varphi m}{}^{*} P_\varphi \right) d\Omega}{\sqrt{\oint \left(X \cdot G_{\theta n} P_\theta + G_{\varphi n} P_\varphi \right) d\Omega \oint \left(X \cdot G_{\theta m} P_\theta + G_{\varphi m} P_\varphi \right) d\Omega}} \tag{2}$$

where E_θ and E_φ are the realized active electric field patterns of the antennas calculated by

$$E_{\theta/\varphi} = \sqrt{G_{\theta/\varphi}}\, \mathrm{e}^{\mathrm{j}\psi_{\theta/\varphi}} \tag{3}$$

where $\psi_{\theta/\varphi}$ are the phase antenna patterns [15, p. 800].

An ultimate metric for the performance of a diversity system is the effective diversity gain (EDG). EDG when defined as the SNR enhancement at a specific outage probability level p% [7] is expressed mathematically by

$$EDG = \left. \frac{x_1}{x_2} \right|_{P(\gamma_D \le x_1) = P(\gamma_0 \le x_2) = p\%} \tag{4}$$

where γ_D and γ_0 are the instantaneous SNRs received by the diversity CPCMEA and an ideal dual-polarized isotropic radiator with unit radiation efficiency [8] which operates in the same propagation environment capturing thus all the available incident power. Assuming a rich scattering environment without a line of sight component, the cumulative density function (CDF) of γ_0 follows the Rayleigh distribution, whiles the CDF of γ_D follows the distribution for MRC signals [16, p. 364]:

$$P(\gamma_D \le x) = 1 - \sum_{m=1}^{M} \frac{\lambda_m^{M-1} \exp(-x/\lambda_m)}{\prod_{n \ne m}^{M} (\lambda_m - \lambda_n)} \tag{5}$$

where λ_m are the eigenvalues of the SNR covariance matrix $\mathbf{\Lambda}$ defined by

$$\lambda_{nm} = \Gamma_0 \rho_{nm} \sqrt{MEG_n MEG_m} \tag{6}$$

where Γ_0 is the average SNR received by the ideal antenna. The mathematical expression in (6) is the generalization of that for two antenna elements presented in [8].

EDG when defined as the SNR reduction for achieving a desired average BER value p [13] is expressed mathematically by

$$EDG = \left. \frac{\Gamma_0}{\Gamma_D} \right|_{\langle P_e \rangle (\Gamma_D) = \langle P_e \rangle (\Gamma_0) = p} \tag{7}$$

where $<P_e>(\Gamma_D)$ and $<P_e>(\Gamma_0)$ are the average BER, which are functions of the average SNR of the diversity CPCMEA and the ideal antenna respectively. In general, $<P_e>(\Gamma)$ is mathematically expressed by [16, p. 469]

$$\langle P_e \rangle (\Gamma) = \int_0^\infty p_e(\gamma) p(\gamma, \Gamma) d\gamma \tag{8}$$

where $p_e(\gamma)$ is the conditional error probability (CEP) of the adopted signaling scheme and $p(\gamma,\Gamma)$ is the probability density function (PDF) of the received SNR. For the MRC scheme the PDF of the combined signal can be found in [16, p. 364].

2.2 MIMO Performance Evaluation

The capacity of a MIMO system, comprising the same number M of transmitting (Tx) and receiving (Rx) antennas, with no CSI at the transmitter and assuming that the transmitted signals are Gaussian distributed with identity covariance matrix and the received ones add coherently at the receiver, is given by [17]

$$C = \log_2 \left(\det \left(\mathbf{I}_M + \frac{P_\mathrm{T}}{\sigma^2 M} \cdot \mathbf{T}\mathbf{T}^\mathrm{H} \right) \right) \tag{9}$$

where det(•) and superscript H denote the determinant and the Hermitian (complex conjugate transpose) of a matrix respectively, P_T is the total input power equally distributed to each Tx antenna's port, σ^2 is the noise power, $\mathbf{I}_\mathrm{M}$ is the

MxM identity matrix and **T** is the transfer matrix of the system.

In order to estimate the transfer matrix **T** of a MIMO system which consists of CPCMEAs at both ends, a modification of the model presented in [10] has been considered. In contrast to this model, however, the spatial differences among the antenna elements are implicitly incorporated in the vectors of the realized active electric field patterns of the Tx and Rx CPCMEAs ($\mathbf{E}_{\mathrm{T}}$ and $\mathbf{E}_{\mathrm{R}}$). Assuming the narrowband transmission case, **T** is expressed by

$$T_{nm} = \sum_{l=1}^{L} \mathbf{E}_{\mathrm{R}_n}(\Omega_{\mathrm{R}l}) \cdot \mathbf{H}(\Omega_{\mathrm{T}l}, \Omega_{\mathrm{R}l}) \cdot \mathbf{E}_{\mathrm{T}_m}(\Omega_{\mathrm{T}l}) \tag{10}$$

where n and m denote the n^{th} Rx and m^{th} Tx antenna ports, L is the number of multipaths, Ω_{T} and Ω_{R} are the direction of departure (DoD) and direction of arrival (DoA) respectively and **H** is a 2x2 matrix describing the $\theta\theta$, $\theta\varphi$, $\varphi\theta$ and $\varphi\varphi$ channel's complex gains

$$\mathbf{H}(\Omega_{\mathrm{T}l}, \Omega_{\mathrm{R}l}) = \frac{1}{4\pi d_l} \begin{bmatrix} a_{\theta\theta l} & a_{\theta\varphi l} \\ a_{\varphi\theta l} & a_{\varphi\varphi l} \end{bmatrix} = \frac{1}{4\pi d_l} \mathbf{a}_l \tag{11}$$

where d_l is the total multipath length assuming specular scattering mechanisms and **a** represents the scattering coefficients matrix [10].

3. Compact Two and Four Printed IFA Antenna Systems

The geometry and dimensions of the investigated compact MEA structures are depicted in Fig. 1. The terminal has typical dimensions of a PC card, whereas the dimensions of the ground plane are 45 mm by 90 mm and consists of two 35 µm thick copper layers with the antennas placed at the upper one and the ground plane at the bottom.

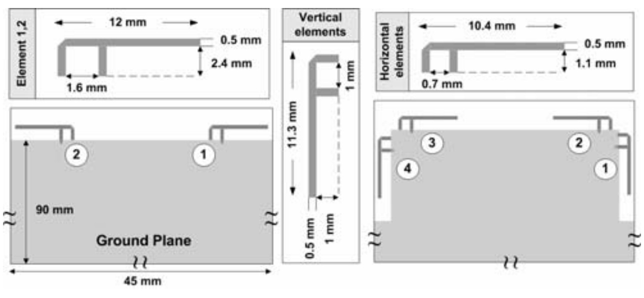

Fig. 1. The layout of the investigated compact common phase center MEA structures.

The antenna elements used are the Inverted F monopoles [18] and were selected due to their compact size, large bandwidth, omnidirectional radiation patterns, no additional fabrication cost and ease of tuning. The antenna elements are printed at the edge of the device's ground plane on an 8 mils-thick substrate with ε_{r}=3.38 and tanδ=0.002, terminated to 50-Ω ports and are well tuned to the 5.2 GHz ISM band [3]. The 3D realized active power gain and phase antenna patterns were computed using the commercial method of moments based EM field solver IE3D [19], assuming source impedances equal to the characteristic impedance of the feeding transmission lines (50 Ω).

4. Simulation Results

In this section the Rx diversity and MIMO performance of the configurations presented in Fig. 1 are evaluated in a uniform and in a single bounce propagation scenario respectively.

4.1 Diversity Performance

In order to calculate the diversity performance of the above described CPCMEA systems, the MEGs and ρ are calculated assuming a uniform propagation environment (X=1 and P_θ=P_φ=1/4π) which is a good approximation to many real environments [4].

Initially, the EDG provided by the two CPCMEAs is calculated in terms of the SNR enhancement at 1% outage probability. The CDFs of γ_{MRC} for the 2- and the 4-port antenna systems are depicted in Fig. 2. The CDF of the Rayleigh distribution and the CDFs of the ideal γ_{MRC} using 2 and 4 equal power and uncorrelated signals [16] are also added in Fig. 2 for comparison. The calculated EDG at 1% outage probability under the MRC scheme are 7.8 (12) and 14.1 (19) dB for the two structures respectively, where the values in the brackets are the EDGs of the ideal systems.

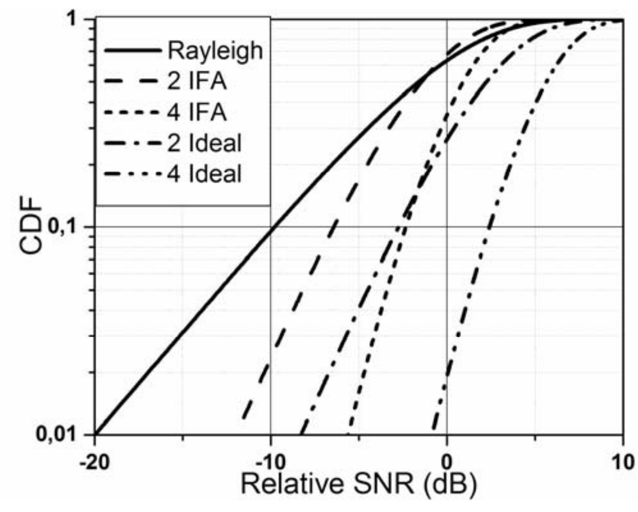

Fig. 2. The CDFs of relative SNR for the reference (Rayleigh), the 2- and 4- IFA and the ideal 2- and 4- branch receive diversity systems.

The EDG provided by the two CPCMEA systems is also calculated in terms of the SNR reduction for achieving a 10^{-4} average BER. The DPSK signaling scheme is employed since it can be used to predict the BER for other schemes with a fair degree of confidence [16, p. 469]. The CEP of DPSK is given by the simple exponential expression $p_e(\gamma) = \exp(-\gamma)/2$ [16, p. 469]. The calculated EDGs for achieving 10^{-4} average BER under the MRC scheme are 14.8 and 23.5 dB for the two structures respectively as extracted from Fig. 3.

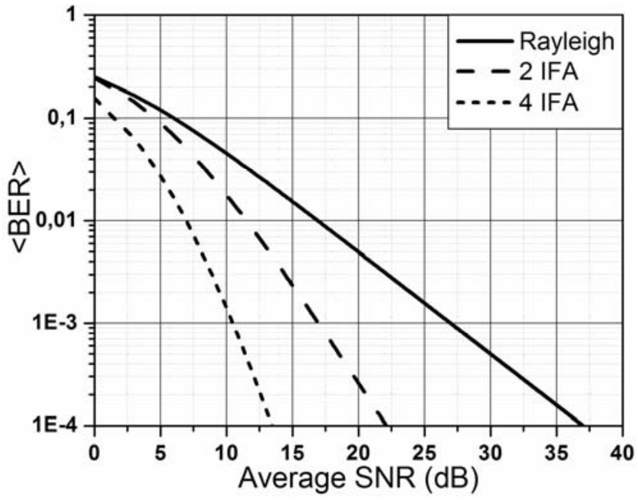

Fig. 3. The average BER versus average SNR for the reference (Rayleigh) and the 2- and 4- IFA receive diversity systems.

4.2 MIMO Performance

By placing two identical MEAs at both ends of a communication link a MIMO system can be formed. The performance of the 2x2 and 4x4 MIMO systems formed in this way is investigated in a hall environment with dimensions 20 m x 30 m x 3.5 m. DoD, DoA and d_l are computed assuming single bounce scattering mechanisms uniformly distributed in the propagation environment with the constraint to reside in the far field region of the Tx and Rx antenna arrays, the phase centers of which are located at (10 m, 10 m, 1.5 m) and (10 m , 20 m, 1.5 m) respectively. The matrix **a** in (11) is calculated assuming that the scattering coefficients are complex Gaussian random variables with zero mean and unit variance [11].

In order to evaluate the capacity of the investigated MIMO systems, the transfer matrix **T** is realized 6000 times assuming L = 21 multipath components [9]. The same P_T/σ^2 is used for all systems, which is selected so that the 1% outage capacity of a SISO system consisting of two vertical dipoles with unit radiation efficiency to be 3.5 bps/Hz. The capacity CDFs for the 2x2 and 4x4 MIMO systems are illustrated in Fig. 4. The 1% outage capacity gains of the investigated MIMO systems over the SISO reference are 5 and 13.5 bps/Hz respectively.

An alternative way to form a MxM MIMO system is by incorporating N>M antennas at the Rx side and selecting from them at each time the optimum M antenna subset using selection algorithms [14]. The reconfigurable MxM MIMO system formed in this way exhibits higher data rates than the corresponding fixed one [14]. In order to illustrate this, consider for instance a MIMO system comprised from the 2- and the 4-port antennas of Fig. 1 at the Tx and Rx sides respectively. By selecting for every channel realization the Rx port pair that provides the highest capacity (reconfigurable 2x2 MIMO system), the 1% outage capacity gain over the fixed 2x2 MIMO system comprised from the 2-element system of Fig. 1 is 3.6 bps/Hz as extracted from Fig. 4 (i.e. a 43% improvement).

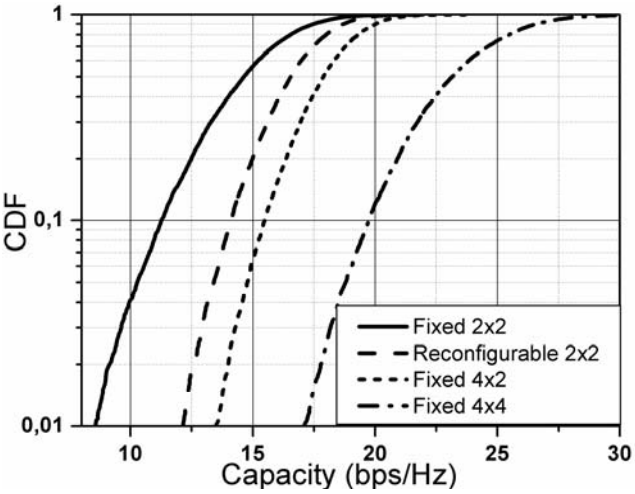

Fig. 4. CDF of the capacity for the fixed 2x2, 4x4, 4x2 and the reconfigurable 2x2 MIMO systems.

5. Conclusions

Diversity and MIMO performance of compact CPCMEA was evaluated in terms of EDG and C using two practical modeling procedures. The calculated EDG under the MRC scheme at 1% outage probability of a two and a four printed IFA structures is 7.8 and 14.1 dB respectively. On the other hand, the calculated EDG for achieving 10^{-4} average BER is 14.8 and 23.5 dB for the two CPCMEAs respectively. The 1% outage C for the fixed 2x2, 4x4, 4x2 and the reconfigurable (under the concept of receive antenna selection) 2x2 MIMO systems are 8.5, 17, 13.5 and 12.1 bps/Hz respectively. The capacity benefits offered by using reconfigurable MIMO systems comes at the expense of a more involved switching circuit, but this overhead is far less than the cost and complexity of additional analog RF chains which, moreover, are difficult to integrate on the restricted space of the user equipment.

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